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# Chapter 7

## Air Distribution and Ventilation Effectiveness in a Room with Floor/Ceiling Heating and Mixing/Displacement Ventilation

Xiaozhou Wu, Lei Fang, Bjarne W. Olesen and Jianing Zhao

**Abstract** The present study investigated different combinations of floor/ceiling heating with mixing/displacement ventilation and their impacts on the indoor air distribution and ventilation effectiveness. Measurements were performed in a room during heating season in December. The results show that indoor vertical air temperature differences and air velocities for different hybrid systems are less than 3 °C and 0.2 m/s when supply air temperature is 19 °C, air change rate is 4.2 h<sup>-1</sup>, and heated surface temperature of floor/ceiling heating system is 25 °C. Ventilation effectiveness of mixing ventilation system combined with floor/ceiling heating systems is approximately equal to 1.0, and ventilation effectiveness of displacement ventilation system combined with floor/ceiling heating systems ranges from 1.0 to 1.2. The floor/ceiling heating systems combined with mixing ventilation system have more uniform indoor air distribution but smaller ventilation effectiveness compared with the floor/ceiling heating systems combined with displacement ventilation system. With regard to the building heat loss increased by non-uniform indoor air distribution and small ventilation effectiveness, there should be an optimal combination of floor/ceiling heating with mixing/displacement ventilation to have the minimal building heat loss.

**Keywords** Floor heating (FH) · Ceiling heating (CH) · Mixing ventilation (MV) · Displacement ventilation (DV) · Air distribution · Ventilation effectiveness

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## 7.1 Introduction

Low-temperature heating systems, such as floor heating systems and ceiling heating systems, are regarded as energy efficient and comfortable heating systems so that they have been extensively used in residential and non-residential buildings [1, 2]. Many energy efficient building technologies involving increased thermal insulation and air tightness have been applied in the low-temperature heating buildings. Unfortunately, these technologies may cause insufficient fresh air to be supplied by infiltration and may thus lead to poor indoor air quality and increased healthy symptom [3]. To avoid this problem, a mechanical ventilation system, such as a mixing ventilation system or a displacement ventilation system, for fresh air supply must be integrated with the low-temperature heating systems.

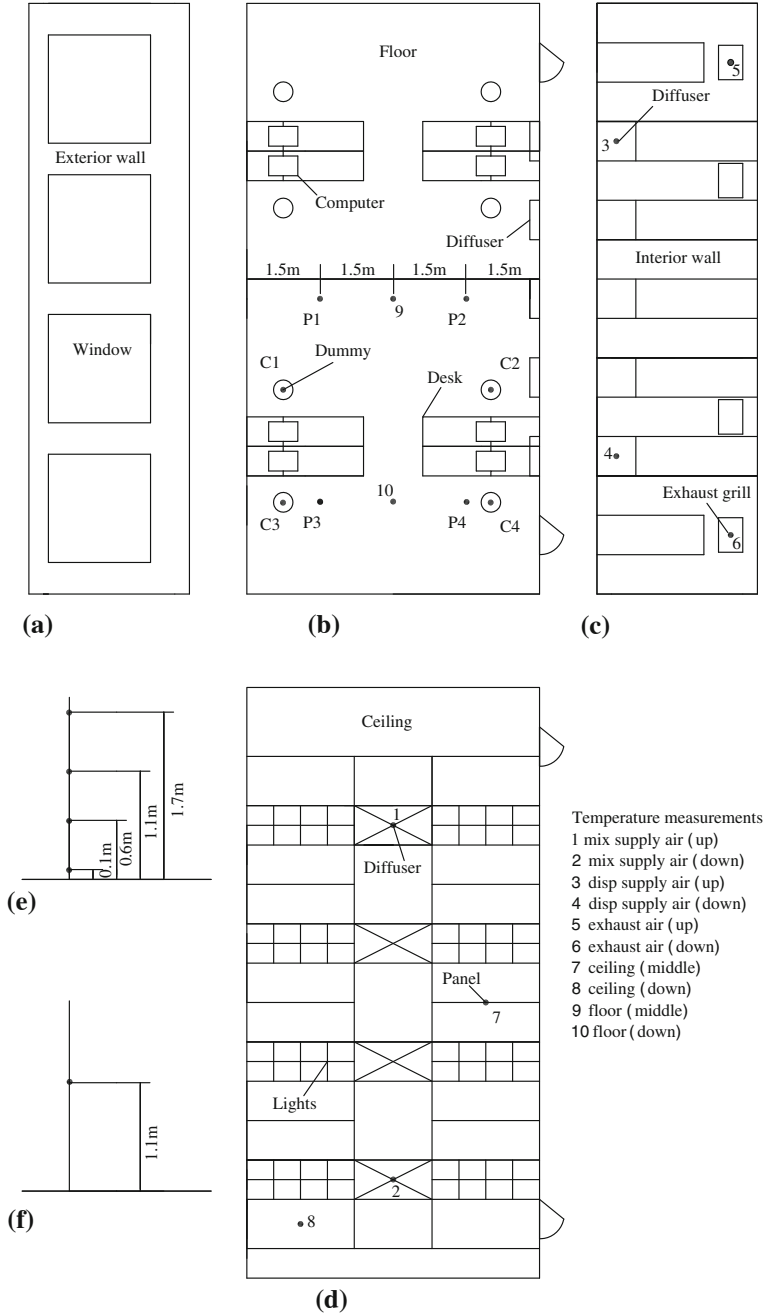
Compared to the low-temperature heating system, a hybrid system with floor/ceiling heating and mixing/displacement ventilation will create a new situation with regard to air distribution and ventilation effectiveness; i.e., the indoor air distribution in a room with floor/ceiling heating systems may be changed by the integration with mixing/displacement ventilation, and the ventilation effectiveness of mixing/displacement ventilation system may be influenced by the integration with floor/ceiling heating systems.

In order to get the optimal hybrid system with regard to the minimal building heat loss, many measurements have been performed in a room with some combinations of floor/ceiling heating with mixing/displacement ventilation [4–7]. Few studies focus on the air distribution and ventilation effectiveness in a room with all combinations of floor/ceiling heating with mixing/displacement ventilation. Therefore, in this paper, all combinations of floor/ceiling heating with mixing/displacement ventilation and their impacts on the indoor air distribution and ventilation effectiveness were investigated.

## 7.2 Methodology

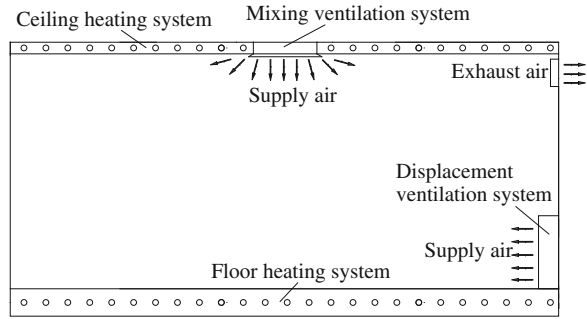
### 7.2.1 Test Room

The room used for the measurements is located on the second floor in building 402 at the International Centre for indoor environment and energy (ICIEE) at Technical University of Denmark (TUD). It is used for regular lectures, occasional meetings, and other events of the ICIEE. In order to simulate the office environment, the room has been rearranged to be an office room for 8 persons in this paper. A schematic outline of the room and the experimental setup is given in Fig. 7.1. The room has an approximate floor area of 72 m<sup>2</sup>. The room's usable height is 2.7 m. The outside wall has a total area of 32.4 m<sup>2</sup>, including a total window area of 13.2 m<sup>2</sup>: four windows with 3.3 m<sup>2</sup> each. The dummies are used to simulate office workers in the experiment. There have been a total of 8 dummies of



**Fig. 7.1** Setup of the test room and location of the sensors. **a** External wall and window. **b** Floor surface. **c** Internal wall surface. **d** Ceiling surface. **e** Vertical air temperature and air velocity measurement point (P1–P4). **f** Contaminant concentration measurement points (C1–C4)

**Fig. 7.2** The schematic diagram of test systems



which were equipped with 80 W light bulbs, resulting in a total power of 640 W. Other internal heat sources in a typical office room, such as computers and lights, have a total power of 1010 W. They were placed in the same locations for each of the measurements.

### 7.2.2 Test Systems

The room is equipped with numerous heating, cooling, and ventilation systems. For this paper, floor heating (FH), ceiling heating (CH), mixing ventilation (MV), and displacement ventilation (DV) were used, as shown in Fig. 7.2.

For displacement ventilation system, air is supplied through supply duct alongside the bottom of the inner wall. For mixing ventilation system, air is supplied through supply duct alongside the ceiling. Air is removed through exhaust ducts below the ceiling in the same wall.

### 7.2.3 Measurement Parameters

Air velocity and temperature were measured with four spherical probes HT-412 that were connected to transducers HT-428-0. The sensors were used with the measuring station HT-480. This equipment is from the company Sensor Electronic. The minimal velocity that can be measured is 0.05 m/s. From 0.05 to 1 m/s, the accuracy is  $\pm 0.02$  m/s or  $\pm 1\%$ . Above 1 m/s, the accuracy is  $\pm 3\%$ . The accuracy of the temperature measurement is  $\pm 0.2$  °C.

Air velocity and temperature were measured in four different heights in each of the locations P1 through P4, as shown in Fig. 7.1b. Since only four anemometers were available, measurements had to be done four times. The arrangement of the sensors on the stand is illustrated in Fig. 7.1e. The duration of one measurement was 10 min. After measurements were completed in one location, the sensors were moved to the next location.

**Table 7.1** Test conditions for different hybrid systems

| Hybrid systems | Supply air temperature (°C) | Reference air temperature (°C) | Ceiling surface temperature (°C) | Floor surface temperature (°C) | Air change rate ( $\text{h}^{-1}$ ) |
|----------------|-----------------------------|--------------------------------|----------------------------------|--------------------------------|-------------------------------------|
| FH + MV        | 19.0                        | 22.0                           | –                                | 25.0                           | 4.2                                 |
| FH + DV        | 19.0                        | 22.0                           | –                                | 25.0                           | 4.2                                 |
| CH + MV        | 19.0                        | 22.0                           | 25.0                             | –                              | 4.2                                 |
| CH + DV        | 19.0                        | 22.0                           | 25.0                             | –                              | 4.2                                 |

Freon as the tracer gas was used to measure the age of air. Concentration measurement and gas dosing in the room were performed through Innova photoacoustic multi-gas monitor. The instrument was placed outside the room. One dosing point and one sampling point were placed in the supply duct and the exhaust duct of ventilation systems, separately. Other four sampling points (C1–C4) were closed to the four dummies at the height of 1.1 m above floor level, as shown in Fig. 7.1b and f.

### 7.2.4 Test Conditions

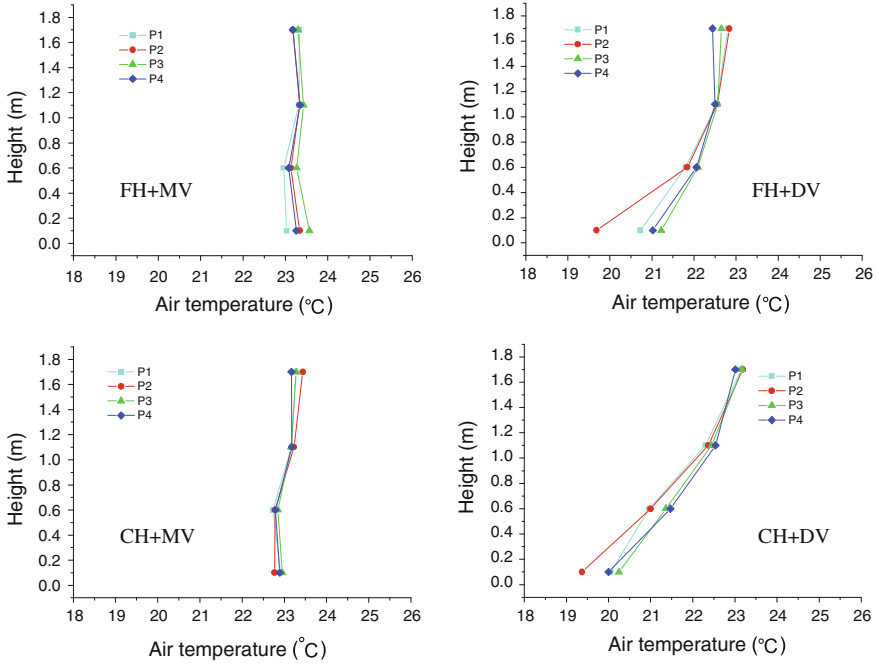
The test conditions for different hybrid systems are shown in Table 7.1, where the reference air temperature and the air change rate refer to the Category I for non-low-polluting building in standard EN 15251 [8].

## 7.3 Results and Discussions

### 7.3.1 Vertical Air Temperature Distribution

Vertical air temperature distributions in a room with different hybrid systems are shown in Fig. 7.3.

Figure 7.3 shows the vertical air temperature distribution in a room with floor/ceiling heating and mixing/displacement ventilation. It shows that floor/ceiling heating systems combined with mixing ventilation system have the more uniform vertical air temperature distribution compared with the floor/ceiling heating systems combined with displacement ventilation system. This is mainly due to the “mixing effect” in the mixing ventilation room and the “buoyancy effect” in the displacement ventilation room. Figure 7.3 also shows that vertical air temperature difference between the head level and the foot level is mostly less than 3 °C, which are within the local thermal comfort range according to ISO 7730 [9].



**Fig. 7.3** Vertical air temperature distribution in a room with different hybrid systems

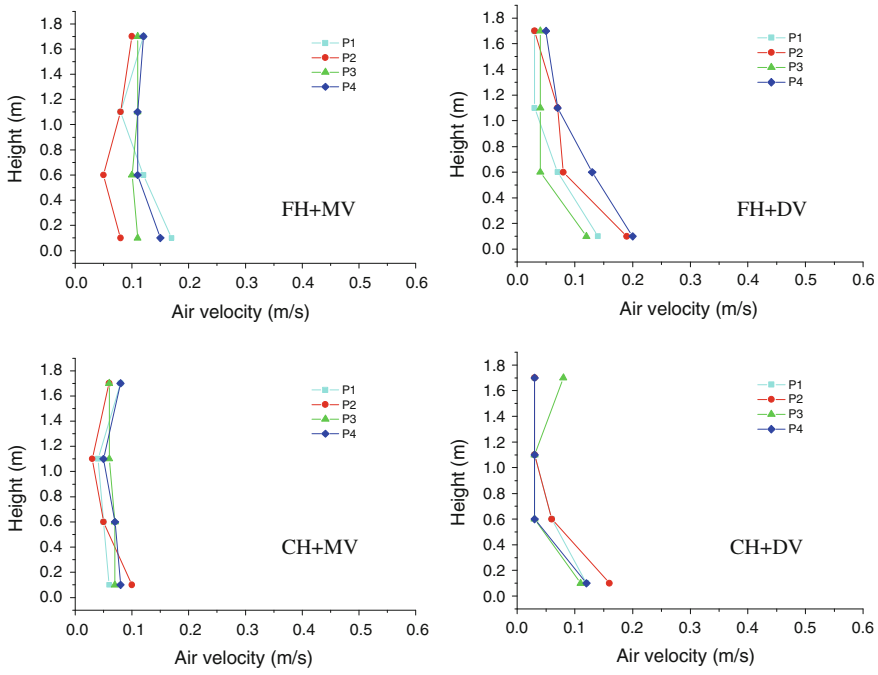
### 7.3.2 Vertical Air Velocity Distribution

Vertical air velocity distributions in a room with different hybrid systems are shown in Fig. 7.4.

Figure 7.4 shows the vertical air velocity distribution in a room with floor/ceiling heating and mixing/displacement ventilation. It shows that the floor/ceiling heating systems combined with mixing ventilation system also have the more uniform vertical air velocity distribution compared with the floor/ceiling heating systems combined with displacement ventilation system. This is also mainly due to the “mixing effect” in the mixing ventilation room and the “buoyancy effect” in the displacement ventilation room. Figure 7.4 also shows that local air velocity are all less than 0.2 m/s, which will not cause any local thermal discomfort in terms of draught when local air temperature are more than 19 °C (as shown in Fig. 7.3).

### 7.3.3 Ventilation Effectiveness

Ventilation effectiveness includes contaminant removal effectiveness (CRE) and air change efficiency (ACE) [10]. CRE indicates the ability of a ventilation system



**Fig. 7.4** Vertical air velocity distribution in a room with different hybrid systems

to remove airborne contaminants, and ACE indicates the ability of a ventilation system to exchange the air in the room. This study mainly focuses on the fresh air supply, so ACE was used in this paper. ACE can be calculated using Eqs. (1–3):

$$ACE = \frac{\tau_n}{\langle \bar{\tau}_p \rangle} \quad (7.1)$$

$$\tau_n = \int_0^{\infty} \frac{c_e(t)}{c_e(0)} dt \quad (7.2)$$

$$\bar{\tau}_p = \int_0^{\infty} \frac{c_p(t)}{c_e(0)} dt \quad (7.3)$$

where  $\tau_n$  is the time constant,  $\bar{\tau}_p$  is the local mean age of room air,  $c_p(t)$  is the instantaneous local contaminant concentration in room, and  $c_e(t)$  is the instantaneous contaminant concentration in exhaust dust.

Table 7.2 shows the ventilation effectiveness in a room with different hybrid systems. It shows that the mean ventilation effectiveness for mixing ventilation system combined with floor/ceiling heating systems are approximately equal to



**Table 7.2** Ventilation effectiveness in a room with different hybrid systems

| Hybrid systems | Measurement points |      |      |      |      |
|----------------|--------------------|------|------|------|------|
|                | S1                 | S2   | S3   | S4   | Mean |
| FH + MV        | 0.99               | 1.00 | 1.00 | 1.00 | 1.00 |
| FH + DV        | 1.17               | 1.12 | 1.20 | 1.05 | 1.14 |
| CH + MV        | 0.97               | 0.99 | 0.96 | 0.96 | 0.97 |
| CH + DV        | 1.02               | 1.04 | 1.09 | 1.08 | 1.06 |

1.0, and the mean ventilation effectiveness for displacement ventilation system combined with floor/ceiling heating systems range from 1.0 to 1.2. This means that the ventilation effectiveness of mixing ventilation system combined with floor/ceiling heating system are equal to the recommended value in ASHRAE standard 62.1 [11], and the ventilation effectiveness of displacement ventilation system combined with floor/ceiling heating system is slightly less than the recommended value in ASHRAE standard 62.1. This may be due to the effect of downdraft caused by cold external envelope surface on the vertical air distribution [12].

It seems that it is contradictory to have the most uniform air distribution and the biggest ventilation effectiveness for one combination of the floor/ceiling heating systems with mixing/displacement ventilation systems. Non-uniform air distribution will increase the building envelope heat loss by increasing the room reference temperature, and the small ventilation effectiveness will increase the ventilation heat loss by increasing the required fresh air supply [13]. Although it is impossible to have the most uniform air distribution and the biggest ventilation effectiveness for one hybrid system, there should be an optimal hybrid system with regard to the minimal building heat loss under certain ratio of building envelope heat loss to ventilation heat loss.

## 7.4 Conclusions

- Air distribution in a room with floor/ceiling heating and mixing/displacement ventilation will not cause any local thermal discomfort in terms of vertical air temperature difference and draught.
- The ventilation effectiveness of mixing ventilation system combined with floor/ceiling heating system are equal to the recommended value in the ASHRAE standard 62.1, and the ventilation effectiveness of displacement ventilation system combined with floor/ceiling heating system are slightly less than the recommended value in the ASHRAE standard 62.1.

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